Available online at www.sciencedirect.com

ScienceDirect

Renewable and Sustainable Energy Reviews
12 (2008) 2177–2193

RENEWABLE & SUSTAINABLE ENERGY REVIEWS

www.elsevier.com/locate/rser

River current energy conversion systems: Progress, prospects and challenges

M.J. Khan*, M.T. Iqbal, J.E. Quaicoe

Faculty of Engineering & Applied Science, Memorial University, St. John's, A1B3X5, NL, Canada

Received 5 April 2007; accepted 16 April 2007

Abstract

River current energy conversion systems (RCECS) are electromechanical energy converters that convert kinetic energy of river water into other usable forms of energy. Over the last few decades, a number of reports on technical and economic feasibility of this technology have emerged. However, the potentials of this technology as an effective source of alternative energy have not yet been explored to a great extent. The underlying challenges of system design, operation and economics also lack proper understanding. In this article, starting with a definition of the RCECS, an overview of the technological advancements in the relevant field is provided. From a system engineering perspective, various merits and prospects of this technology along with pertinent challenges are discussed. The cross-disciplinary nature of approaching these challenges with an emphasis on the need for contributions from various technical and non-technical domains are also outlined in brief. This article may serve as a coherent literature survey or technology review that would provide better understanding of the subjacent issues and possibly rejuvenate research interest in this immensely potential field of energy engineering.

Keywords: River turbine; Emerging technology; Literature; Technology survey

Contents

*Corresponding author. Tel.: +1 709 737 2049; fax: +1 709 737 4042.
E-mail addresses: mjakhan@engr.mun.ca (M.J. Khan), tariq@engr.mun.ca (M.T. Iqbal), jquicoe@engr.mun.ca (J.E. Quaicoe).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2007.04.016

1. Introduction

A river current energy conversion system (RCECS) could be defined as an electromechanical energy converter that employs a RCT to harness the kinetic energy of river water. Radkey and Hibbs [1] defined river current turbines as 'Low pressure run-of-the-river ultra-low-head turbine that will operate on the equivalent of less than 0.2 m of head'. Conventional large or small hydroelectric systems use reservoirs and penstocks to create an artificial water head and extract the potential energy of downwardly falling water through suitable turbomachinery. In contrast, a river turbine, which could be built as a free-rotor or part of a channel augmented system, may provide an effective alternative mean for generating power. Such systems would potentially require little or no civil work, cause less environmental impact, and may possess significant economic value.

The term RCECS is interchangeable with other similar technologies often mentioned in the literature. Terms such as water current turbine (WCT) [2], ultra-low-head hydro turbine [1], hydrokinetic turbine [3], free flow/stream turbine (implying use of no dam, reservoir or augmentation) [3], zero head hydro turbine [2,4], are common and employ the same underlying principle of operation. In this article, the term RCECS, 'river current turbine (RCT)' will be used extensively, occasionally using the other terms.

The study of several allied fields such as, tidal energy, marine current energy and most importantly wind energy can be considered valuable in developing an understanding of the

RCECS technology. These turbines work on the same principle, where kinetic energy of the streaming fluid is utilized to rotate an electromechanical energy converter and subsequently generate electricity. The governing equation in such energy conversion is

$$P = \frac{1}{2}\rho A V^3 C_p, \quad (1)$$

where P is the mechanical power extracted by the turbine (W), ρ is the density of the fluid (1000 kg/m^3 for water and 1.223 kg/m^3 for wind, approximately), A is the area of the rotor blades (m^2), V is the fluid velocity (m/s), and C_p is the power coefficient, a measure of the fluid-dynamic efficiency of the turbine.

A brief comparison of wind and hydro turbines provides a better insight into the energy-capacities of these systems (Fig. 1). Wind turbines are usually designed to operate with rated wind speed of 11–13 m/s. In contrast, river turbines with augmentation channels (to elevate the total volumetric water flow and subsequent power output) could be designed for effective water velocities of 1.75–2.25 m/s or even higher, depending on site resources. This indicates the possibility of higher energy capacity through a river turbine when compared to an equally sized wind energy converter (Fig. 1).

Although sound in theory, practical implementation and performance analysis toward designing a cost-effective system and displaying its effectiveness is subject to indepth investigation, research and entrepreneurial venture. Evidently, to date, most investigations have been carried out emphasizing the mechanical design aspects of turbine rotors and the like. A comprehensive source of information, relating the past, present and possible future of this technology, especially in the public domain, is almost non-existent. The purpose of

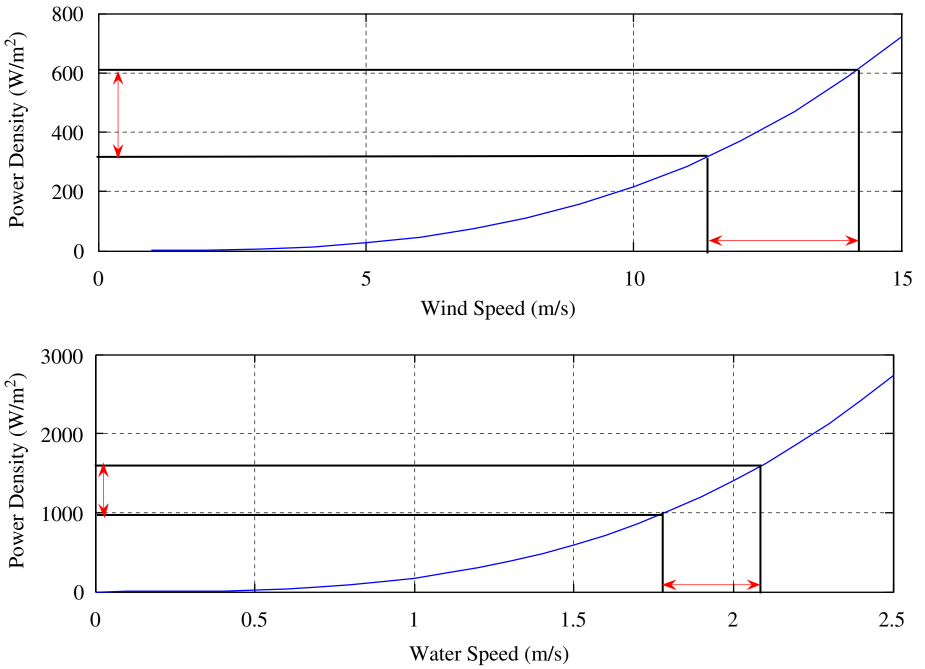

Fig. 1. Power density of wind turbine and channel augmented river turbine ($C_p = 0.35$).

this article is to organize the available literature, give insight into the challenges and possibly rejuvenate discussions in this promising field.

2. Survey of technological progress

A brief historical perspective of hydropower utilization would facilitate a chronology of advent and progress of RCECS technologies. Men have utilized the force of moving river water to their benefit for centuries. During the 3500 BC, boats were the principle means of transportation in the Tigris and the Euphrates Rivers for commerce between far-flung regions. The Mesopotamian civilization relied heavily on such methods of transportation. These vehicles relied on the energy in moving water to provide motion [5]. During the period of 500–900 AD, different variants of undershot water wheels began to appear in various parts of the world. Irrigation for agriculture, milling of food grains, and supply of fresh water depended greatly on such machines [6]. As the modern civilization realized the great need and benefit of electrical power, hydroelectricity started to play a major role in power generation during the mid-nineteenth century. Subsequently, small to large-scale plants consisting of dams, reservoirs and turbomachinery started to appear all around the world [7]. Although economic success geared the installation of hundreds of large hydroelectric systems, bio-adversity and inauspicious ecological impacts have been an ever-impeding issue.

Based on the available formal literature, the very first example of RCT that was developed and field tested is attributed to Peter Garman [2,8,9]. An initiative by the Intermediate Technology Development Group (ITDG) in 1978 resulted in the so-called *Garman Turbine* specifically meant for water pumping and irrigation. Within a period of four years, a total of nine prototypes were built and tested in Juba, Sudan on the White Nile totaling 15,500 running hours. Experience gained during this venture indicated favorable technical and economical outcome. Initial designs had a floating pontoon with completely submerged vertical axis turbine, moored to a post on the bank. Later designs consisted of an inclined horizontal axis turbine with almost similar floatation and mooring system (Fig. 2(a)). Detailed investigation on a low cost water pumping unit indicated 7% overall efficiency and concluded with emphasis on societal and cost issues [2]. More recent commercial ventures resulting from this work are being pursued by Thropton Energy Services [10], Marlec Engineering Co. Ltd. [11,9], and CADDET Center for Renewable Energy [12].

Research results on similar inclined axis turbines have been reported in [13,14]. In these works, the feasibility of utilizing river energy in Bangladesh were studied, and great details and conclusions were drawn in favor of such technologies. The effects of varying blade pitch and shaft inclination angle were also studied and an average mechanical system efficiency of 30% was reported.

Another Australian design (Alternative Way, Nimbin, Australia) known as *Tyson Turbine* consisted of a horizontal axis rotor with a submerged 90° transmission mechanism that powers a generator fitted on a pontoon [15](similar to Fig. 2(b)). A Belgian concept (Rutten Company, Herstal, Belgium) containing a twin tubular pontoon with floating turbine and a straight bladed waterwheel was tested in Zaire, Africa [16] (Fig. 3(a)). Information on several similar designs with horizontal and vertical axis rotors that were tested in the Amazon regions of Brazil could be found in [3]. This report emphasizes the success and robustness of the tested hydrokinetic turbine system for use in remote

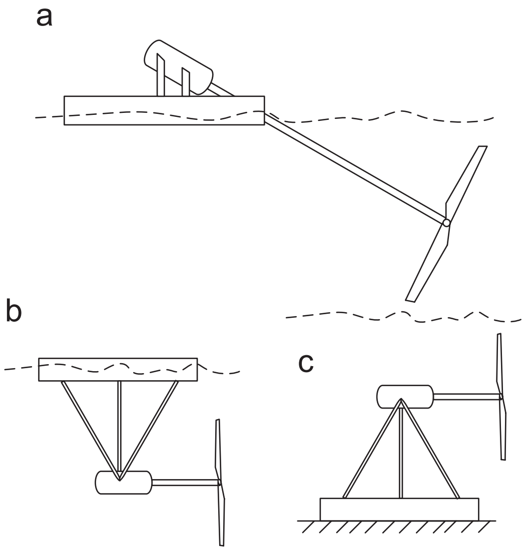

Fig. 2. Axial flow water turbines: (a) inclined axis, (b) float mooring; (c) rigid mooring.

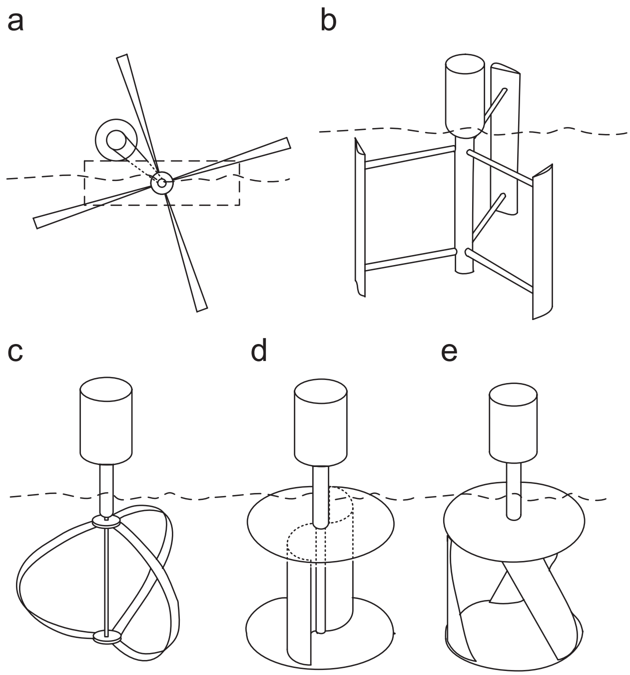

Fig. 3. Cross flow turbines: (a) in-plane, (b) H-Darrieus, (c) Darrieus, (d) Savonious, (e) helical.

locations. The need for protection mechanisms against debris and severe conditions has also been outlined. However, technical information on these designs and their performance is not available.

A substantial work carried out by Environment Inc. under the US Department of Energy's ultra-low-head hydro energy program during the early 80s is reported in [1]. In this project, an assessment of river resources in various rivers in the United States was extended for cost analysis and experimentation of river turbines. A free rotor (15 kW at 3.87 m/s, 3.05 m dia.) and a duct augmented (20 kW at 2.13 m/s, 3.05 m dia.) turbine with submerged horizontal axis rigid pontoon configuration (Fig. 2(c)) were studied and experiments were carried out with a smaller unit. With different duct geometries, power coefficients from 0.66 to 1.69 were achieved, which is well beyond the theoretical Betz limit and hence, very encouraging from performance point of view. This venture concludes that river turbines can be cost effective when placed in resourceful sites. The addition of an augmentation channel would increase the energy yield at the price of higher technical risk. However, details of the electromechanical energy conversion were not discussed and no active control method was incorporated.

Technological advancement in tidal energy conversion, which employs the same principle as river turbines, is rather mature. RCECSs are being proposed as small power units with floating structures that can be easily placed in a river channel. In contrast, tidal turbines are generally larger in size, rigidly moored, and operate under periodic tide motion. Nevertheless, information on tidal energy systems is extremely valuable in understanding the river turbine technology.

In the commercial domain, various river/tidal energy converters have been emerging since the early 1990s. UEK Corporation in the United states have been developing diffuser augmented solid pontoon river/tidal turbines under the brand name of *Underwater Electric Kite* [17,18]. One of the most significant success stories of tidal energy conversion comes from the Marine Current Turbines Ltd.'s (MCT) field test in the coast of Devon, Southwest England [19,20]. Their design consists of a 300 kW, twin bladed pitch actuated system. Newer designs with two turbines on the same tower are being proposed by MCT. SMD Hydrovision in England has also successfully tested their twin turbine model named *TidEL* with a 1:10 scale unit at the New and Renewable Energy Centre (NaREC) in Blyth, UK [21]. This employs a floating structure moored to a fixed support. A Norwegian design by Hammerfest Strom with design similar to MCT turbines has also been tested and attempts for commercialization are in progress [22]. Manufacturers such as, HydrVenturi [23], and Lunar Energy Limited [24] have been attempting underwater tidal converters with augmentation mechanisms. VerdantPower LLC in the US [25] and J. A. Consultant [26] in the UK have designed smaller units of submerged propeller type turbines. Innovative designs named as Stingray (by The Engineering Business Limited [27]) and Sea Snail (by Robert Gordon University [28]) have also gained significant public attention. Most of these designs are patented technologies meant for large scale tidal energy conversion. Design and performance data of these systems and information on usability as river turbines is not available in the public domain.

A valuable piece of literature on controller synthesis and maximum power extraction of a small propeller type tidal turbine is found in [29]. In this work, Tip Speed Ratio (TSR) of a turbine is assessed and a PID type controller was used to control a dump load and achieve maximum power output. A power coefficient between 20% and 30% has been reported and further investigation of blade pitching mechanism was proposed.

Apart from the axial flow turbines surveyed in the above section, cross flow turbines (Fig. 3) have also shown good promise. Perhaps the most detailed design, testing and entrepreneurial efforts toward realizing vertical axis turbines for tidal energy conversion

was carried out by Barry Davis and his business concern Blue Energy Canada Inc. [30–32]. To date six prototypes including model names such as: 20 kW B1, 100 kW B2, 4 kW VEGA, and 5 kW TOR5 were field tested and results were considered as encouraging. The use of augmentation devices (namely, *Tidal Fence*) was proposed and experiments had indicated nearly 45% system efficiency.

Alternative Hydro Solutions Ltd. in Ontario [33] has recently developed vertical axis turbines specifically meant for river applications. Attempts on designing variable pitch vertical turbines, namely, *cycloidal turbines* have been reported by Verdant Power LLC [25] and Environmental Turbine Technology development (ETTE Elektro, Norway) [34].

Public domain literature on vertical axis hydrokinetic turbine design is numbered. Nevertheless, recent publications have indicated greater interest in this field, especially for tidal energy applications. A report on diffuser augmented vertical axis H-Darrieus turbine found in [35] indicates 35% efficiency. In conclusion to this work, promises of ducted water current systems have been boosted and further investigation was encouraged.

A substantive series of works on Darrieus type turbine design and their performances is done by Kiho et al. at the Nihon University, Japan [36–40]. Comparison of H-Darrieus turbines against Savonious configuration can be found in [37,38]. Although the latter type can run on lower TSR and hence self-start, Darrieus turbines were observed to be of higher efficiency. In [36,38], report of a 5 kVA turbine with overall system efficiency of 55% could be found. A very good analysis of Darrieus turbine design, torque ripple and insight into the starting torque problem can also be found in [39,40]. The effect on system performance due to varying solidity, number of blades and blade inclination angle were also studied as part of this investigation.

In [41] an analysis of direct drive permanent magnet generators for use in underwater turbines is presented. Fluid dynamic analysis and discussions on design of variable pitch H-Darrieus turbines can be found in [42,43].

A recent design by Alexander M. Gorlov developed at the Northeastern University, Boston, USA has gained significant attention for both river and tidal applications. The so-called *Gorlov Helical Turbine*, *GHT* employs twisted blades with helical curvature. Better modularity, scalability and economics have been claimed in favor of this design [4,44–46].

Various other methods of harnessing energy from moving water stream have been emerging in recent times. Florida Hydro Ltd. is experimenting with a new concept of open channel turbine [47]. Detailed information on performance and design of such turbine has not been made public. Researchers at the Mie University, Japan are experimenting with various hydro turbine concepts such as: Orhotpetre and Gate type turbines [48]. However, results on the tests of their design could not be gathered. Methods of energy conversion by means of piezoelectric materials are being experimented at the Ocean Powers Technologies Inc., NJ, USA. Apart from some small-scale experiments, this concept has not been entirely demonstrated [49]. A unique and rather dubious concept (known as *Transverpello*) is being pursued by an individual in Munich, Germany [50]. This concept employs flapping motion of a single blade, which is coupled with linear electromechanical devices. A conceptual outline of electricity production utilizing salinity gradients at river-sea concourses is discussed in [51]. Further literature on vertical axis turbines, augmentation and zero head hydro propulsion system could be found in [52–55].

3. Prospects and merits

The demand for cheap and environmentally friendly source of energy is expected to increase significantly. United States Energy Information Administration predicts that a 73% increase in world electricity consumption is expected between 1999 and 2020 making electricity the fastest-growing energy industry [56]. Consequently, advances in various alternative fields of energy technologies such as, wind, solar, micro-hydro and fuel cell systems have received significant attention in recent years. RCECSs, if proven to be a cost-effective and viable option, may become a new member in the renewable energy family.

3.1. Rural electrification in developing countries

It is believed that many developing countries such as, China, India, and Brazil will appear as the key drivers behind the boost in energy demand in future. However, according to the United Nations Development Program (UNDP, 2002), over 2 billion people have zero access to electricity, 1 billion people adopt mundane power sources (dry cell batteries, candles and kerosene) and 2.5 billion people in developing countries, mainly in rural areas, have marginal access to national electricity grid [56]. Such a contrast implies an acute need for suitable energy option for rural areas in the developing world.

Historically, rivers have played a paramount role in shaping and sustaining civilizations. Most of the populous areas in the world have a river in their proximity providing a source of fresh water, food and transportation. Many developing countries are crisscrossed with rivers carrying significant volume of water round the year. An effective and low-cost mechanism for harnessing energy from the flowing river may revolutionize the scenario of rural power generation.

A brief look at the world atlas reveals an interesting correlation between population, need for electrification, poverty and river distribution [57]. This match is more dominant in Asia, Central Africa and South America. A detailed quantitative analysis with global perspective may point to significant socio-economic importance of river as a source of energy.

3.2. Impact on environment

In contrast to large or micro hydro turbines, RCECSs could be used as distributed systems installed over a large river basin area. Therefore, environmental adversities attributed to the former group are expected to be minimal for the proposed case. However, a thorough investigation on turbine usage and its effect on natural flow of the river, impact on river course, ecosystem, and wildlife would only reveal the true extent of such assumption.

3.3. Use of available technologies

Most of the components (blade, generator, power converter, etc.) needed for designing a turbine system are mostly readily available. Therefore, product development cycle, cost and level of technical sophistication are expected to be low for this technology.

3.4. Minimal need for civil engineering work

River turbines are generally being proposed as modular and small power sources placed close to the end user. Subsequently, the need for civil engineering work would be minimal compared to conventional large and micro hydroelectric systems, where the construction of dams and waterway consumes significant resources.

3.5. Unidirectional operation and less flow variation

Unlike wind energy, river flow is more predictable and flow variation is in the interval of hours or days. Therefore, the need for fast acting control and protection method is less stringent. Wind direction sensing and turbine alignment is a must for wind turbines. In contrast, water flow in a river is unidirectional and placement of a turbine with fixed orientations would suffice most applications.

3.6. Use of channel augmentation

Channel augmentation schemes concentrate the flow of fluids around a turbine and permit higher level of energy extraction. Although, sound in principal, applications of such devices were not successful in wind turbines owing to many practical challenges such as, tower-head placement, variable orientation, weight and size. Channel augmentation in river turbines appears more suitable as it needs no change in direction, could be placed under water and the structure itself may work as a flotation device.

3.7. Noise and aesthetics

Wind energy, as an emerging technology has been facing significant societal resistance due to concerns of noise pollution and aesthetic displeasure. Underwater installation of a turbine, away from public places would cause no noise disturbance and have zero visual impact. Unlike large hydro systems, impact on river navigation, swimming and boating is expected to be minimal.

3.8. Diversity of application

Electricity production would be the foremost choice of application for a RCECS. Depending on the availability of a power grid, standalone or distributed power generation schemes could be adopted. These turbines could potentially provide several services such as, water pumping for storage, livestock, human consumption, small industry and irrigation. In such applications, water pumps could be employed instead of electrical generators, to facilitate direct mechanical energy conversion.

3.9. Appropriate technology

RCECSs can be possibly built, operated and maintained using local resources and skills. With proper low-tech design and financing mechanism, such turbines may appear as appropriate technologies in developing countries.

4. Challenges

As an emerging alternative source of energy, the challenges against RCT technology are immense. Success of any such technology does not depend entirely on one particular index. Rather, an array of technical and non-technical issues may question its effectiveness. In this section, a wide and general perspective of such underlying challenges is put forward. RCTs with vertical axis configuration are emphasized and electrical power applications are the primary considerations.

4.1. Resource assessment

Perhaps the first and foremost inquiry toward RCT technology raises the question: are there enough resourceful sites around the world to extract energy in an economic manner? If such sites were available, what would be the definition of a 'resourceful site'? This necessitates an investigation of macro and micro scale site assessment, determination of annual energy yield and analysis of river characteristics. Temporal and spatial flow properties of a river along with analysis of river depth, cross section, transport, navigation and aquatic life is also needed. Global river databases are not readily usable for river energy analysis. Therefore, methods of database analysis need to be developed.

4.2. Economics

The subsequent issue, which is also the most dominant factor affecting the success of most energy technologies is the 'cost of energy'. A subset of this index may comprise elements such as: capital cost, operations and maintenance cost, design simplicity, diversity of applications, modularity, scalability, material and labor engagement, and availability of off-the-shelf components. Several other factors that may have indirect impact on the cost are, system reliability (operations under regular and severe conditions), societal acceptance (visual impact, policy support and public attitude) and system performance (efficiency and controls).

4.3. Environmental adversity

Thorough assessment of environmental impacts posed by a river turbine system should also form the basis of its effectiveness as a sustainable technology. Factors such as down-stream flow alterations, adversities on aquatic plant and animals should be brought into light.

4.4. System design

The optimum design of a RCECS is a significant technical challenge. From cost and performance point of view, simple design using off-the-shelf materials is desirable. An outwardly view of a generic channel augmented RCECS is shown in Fig. 4.

A probable complete unit would require a variety of components such as, rotor, channel augmentation, mounting, flotation, mooring, drivetrain, power converter, control instruments and protection devices. Selecting an optimum rotor configuration amongst a variety of horizontal and vertical axis types is a problem by its own merits. The number

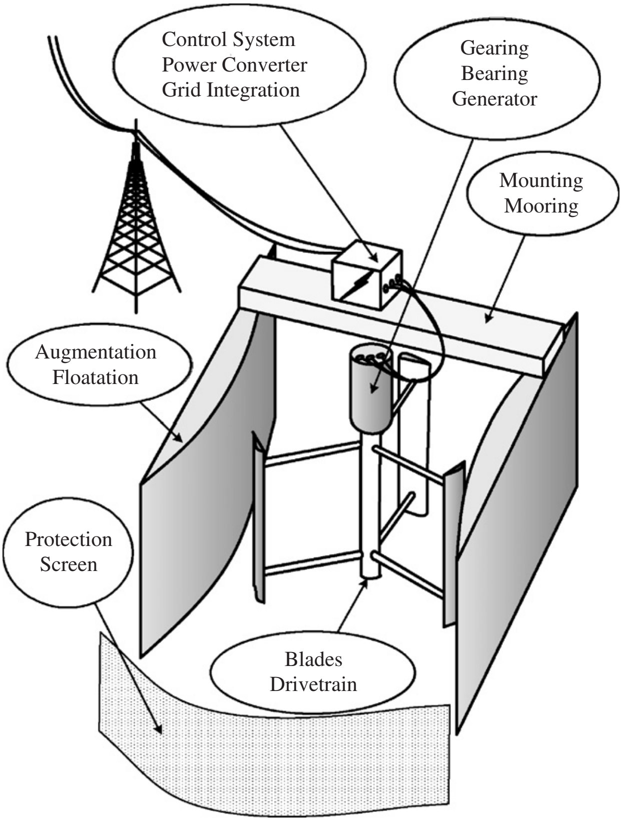

Fig. 4. River current energy conversion system sketch.

of blades, blade materials, design of a proper drivetrain with suitable gearing and bearing mechanism is also of due interest. Since these turbines are exposed to water and run on lower speed, selection of an electrical generator from asynchronous, synchronous, dc and brushless dc categories requires indepth understanding of cost and performance indices of electric machines. Integrating these parts with the flotation/augmentation mechanism and designing a complete system requires structural and reliability analyses.

4.5. Control and operation

For a given system, effective control and operation toward optimizing the system performance is another challenge that requires critical attention. Determination of the control challenges and control regions of such turbine system is a research field by its own merit. However, in line with the wind energy systems, the control problem could be hypothetically formulated through three stages of turbine operation as shown in Fig. 5.

4.5.1. Start up

Axial flow turbines are self-starting and the issue of start up is not significant. However, they come with a price of higher system cost owing to the use of submerged generator or

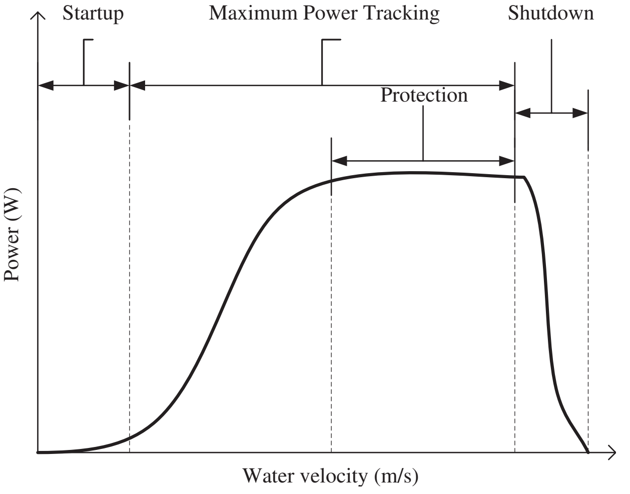

Fig. 5. Control stages of river current energy conversion system.

gearing equipment. Vertical axis turbines, especially the H-Darrieus types with two/three blades are reasonably efficient and simpler in design, but inherently not self-starting. Mechanisms for starting these rotors from a stalled state could be devised from mechanical or electromechanical perspectives. However, an optimum start-up method that would reduce the system complexity and maximize its performance is yet to be engineered.

4.5.2. Maximum power tracking

While the turbine is in the running mode, the control objective is to maximize the extracted energy. Although sufficient technical information is available in the wind-engineering domain, investigation of electrical power generation using active control of river turbine systems is almost absent. Two generic control methods used in wind turbines, namely, stall and pitch control, could be studied to understand the effectiveness of a controlled system. Another possible but untried control approach could be the use of variable geometry augmentation or active augmentation. Realization of these maximum power extraction methods is also closely related to design and control of power electronic stage. Standalone or grid connected mode of operation is also achieved through proper control of the power stage. Performance of a controlled system under real-world conditions such as partial water flow, transported particles and severe condition need also to be investigated.

4.5.3. Protection and shutdown

Over-speed protection during a surge in water velocity beyond the rated speed, and physical armoring from transported materials (debris, snow, rocks, fish, etc.) is a vital part of durability of the system. Additional measures for providing passage for navigation, boating and swimming should also be incorporated in control designs. During severe operating conditions or turbine maintenance, proper shutdown procedures need to be adopted.

4.6. Knowledgebase

At the present state of RCECS technology, the greatest challenge is the lack of sufficient information and scarcity of knowledgebase. Apparently, the technology is struggling to come out of the mechanical design of rotor/augmentation part, let alone demonstrating its overall effectiveness. Just as the challenges are diverse, a multidisciplinary approach is required in order to address these challenges. A brief list highlighting the need for contributions from civil, mechanical and electrical engineering domain is given below:

4.6.1. Civil engineering

- Hydrology, siting, and mooring.
- Environmental impact assessment.
- Commissioning.

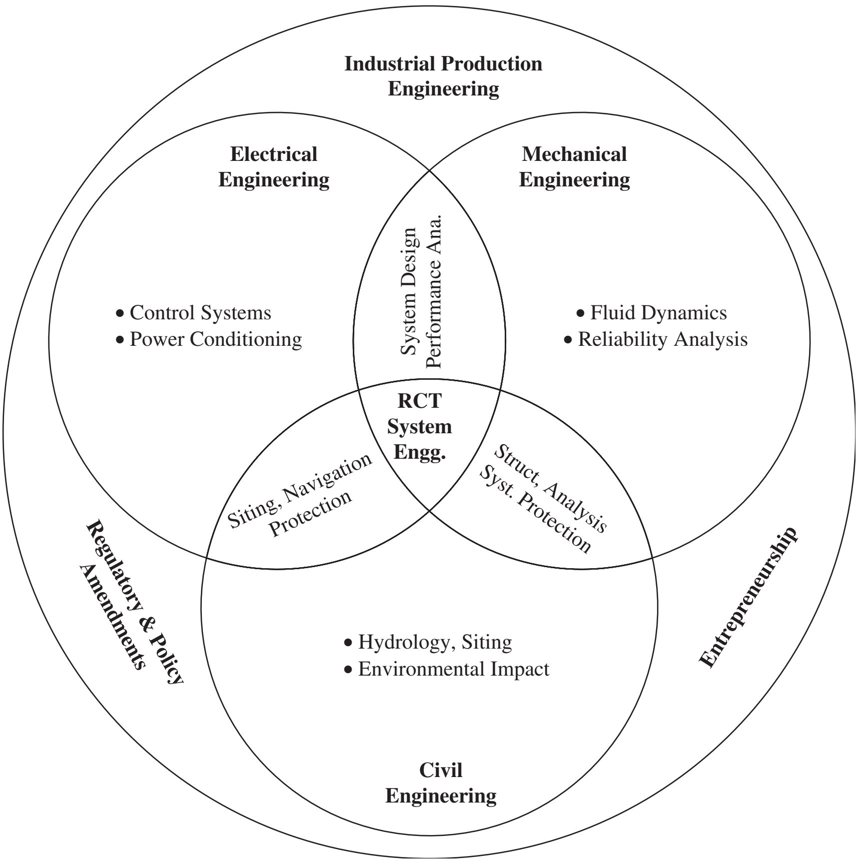

Fig. 6. Cross-disciplinary issues in RCECS system engineering.

4.6.2. Mechanical engineering

- Design of turbine rotor.
- Design of channeling device.
- Structural analysis, fatigue, stiffness and resonance.
- Floatation.
- Water sealing.
- Blade cavitation and bio-fouling.

4.6.3. Electrical engineering

- System design.
- Low speed electrical generator.
- Turbine control (pitch, stall, etc.).
- Augmentation control.
- Stand-alone/grid connected operation.
- Cabling, safety and power electronics.

All these areas of studies need to be shielded by an umbrella of policy support, funding, aggressive entrepreneurship and industrial scale production. Also the economics of the technology (life cycle analysis, cash flow studies, etc.) and contributions from other relevant fields need to be integrated in the design and marketing phase (Fig. 6).

5. Conclusion

The river current energy conversion system technology is probably at its infancy. A set of more recent reports indicate that such devices are slowly entering into the implementation phase, graduating from the laboratory environment [58,59]. However, most of the sporadic efforts in this field have shown encouraging results. To date, the available public domain information mostly relate to mechanical designs of turbine/augmentation units. In order to demonstrate the effectiveness of a complete system, the design of prototypes with electrical interfaces (especially, control and power stages) need to be embarked on. Eventhough the literature survey presented in this work is somewhat exhaustive, discussions on challenges and system engineering is by no means complete. A statement by Barry V. Davis, veteran of tidal energy engineering, summarizes the canonical truth behind such emerging technologies: "It is clear to us that new paradigms meet resistance from the old ...Overcoming this challenge takes extraordinary commitment and resolve on the part of the proponents".

Acknowledgments

The authors would like to thank the Faculty of Engineering & Applied Science at the Memorial University of Newfoundland, Natural Sciences and Engineering Research Council (NSERC), and Atlantic Canada Opportunity Agency (ACOA) for their support.

References

[1] Radkey RL, Hibbs BD. Definition of cost effective river turbine designs. Technical Report AV-FR-81/595 (DE82010972), Report for U.S. Department of Energy, Aerovironment Inc., Pasadena, California, December 1981.
[2] Garman P. Water current turbines: a fieldworker's guide. UK: Intermediate Technology Publishing; 1986 ISBN: 0946688273.
[3] Geraldo L, Tiago F. The state of art of hydrokinetic power in Brazil. International Small Hydro Technologies, Buffalo, NY, USA, 2003, pre-conference Workshop.
[4] Gorlov AM. Harnessing power from ocean currents and tides. Sea Technol 2004;45(7):40–3.
[5] Hunsen RD. Water wheels, February 2007. URL ⟨http://www.waterhistory.org/histories/waterwheels/⟩.
[6] Hazen TR. A history of the water wheel, February 2007. URL ⟨http://www.angelfire.com/journal/millbuilder/historical.html⟩.
[7] Nash L. The changing experience of nature: historical encounters with a northwest river, February 2007. URL ⟨http://www.historycooperative.org/journals/jah/86.4/nash.html⟩.
[8] Dunn PD. Renewable energies: sources, conversion and application. UK: Peter Peregrinus Ltd.; 1986 ISBN: 0863410391.
[9] Garman P. Water current turbines: providing pumping, power in remote areas. Hydro Rev Worldwide 1998;6(5):24–8.
[10] Thropton Energy Services, Physic Lane, Thropton, Northumberland NE65 7HU, United Kingdom, February 2007. URL ⟨http://ourworld.compuserve.com/homepages/throptonenergy/homepage.htm⟩.
[11] Marlec Engineering Co Ltd., Rutland House, Trevithick Rd, Corby Northants, NN17 5XY, February 2007. URL ⟨http://www.marlec.co.uk/index.htm⟩.
[12] CADDET Centre for Renewable Energy, ETSU, Harwell, Oxfordshire OX11 0RA, UK, February 2007. ⟨http://www.caddet-re.org⟩.
[13] Al-Mamun NH. Utilization of river current for small scale electricity generation in Bangladesh. Master's thesis, Department of Mechanical Engineering, BUET, Dhaka, July 2001.
[14] Sadrul Islam AKM, Al-Mamun NH, Islam MQ, Infield DG. Energy from river current for small scale electricity generation in Bangladesh. In: Proceedings of the renewable energy in maritime island climates, Solar Energy Society, UK; 2001.
[15] Levy D. Power from natural flow at zero static head. Int Power Generation.
[16] Rutten L. Au fil de l'eau, une roué a aubes. Systemes Solaires 1994;100:103–5.
[17] UEK Corporation, Abacus Controls, Annapolis, MD 21403, USA, February 2007. URL ⟨http://uekus.com/index.html⟩.
[18] Vauthier P. The underwater electric kite east river deployment. In: Proceedings of A partnership of marine interests OCEANS '88, vol. 3; 1988. p. 1029–33.
[19] Lang C. Harnessing tidal energy takes new turn: could the application of the windmill principle produce a sea change? IEEE Spectr.
[20] Marine Current Turbines Ltd, The Court, The Green Stoke Gifford, Bristol, BS34 8PD, UK, February 2007. URL ⟨http://www.marineturbines.com/home.htm⟩.
[21] SMD Hydrovision, Wincomblee Road, Newcastle upon Tyne NE6 3QS, UK, February 2007. URL ⟨http://www.smdhydrovision.com/products/?id=27⟩.
[22] Hammerfest STRM AS, Norway, February 2007. URL ⟨http://www.tidevannsenergi.com/index.htm⟩.
[23] HydroVenturi Ltd, South Kensington, London, UK SW7 1NA, February 2007. URL ⟨http://www.hydroventuri.com/⟩.
[24] Lunar Energy Limited, Parkgate House, Hesslewood Country Office Park, Ferriby Road, Hessle, East Yorkshire, HU13 0QF, UK, February 2007. URL ⟨http://www.lunarenergy.co.uk/contact.htm⟩.
[25] Verdant Power, LLC, Arlington, VA 22207, USA, March 2007. URL ⟨http://www.verdantpower.com/Initiatives/eastriver.shtml⟩.
[26] J A Consult, London W4 2AF, UK, August 2006. URL ⟨http://www.windenergy.co.uk/framestidal.htm⟩.
[27] The Engineering Business Limited, Northumberland, NE44 6EG, UK, February 2007. URL ⟨http://www.engb.com/services.html⟩.
[28] Robert Gordon University, U.K.; ⟨http://www.rgu.ac.uk/cree/general/page.cfm?pge=10769⟩ February 2007.
[29] Tuckey AM, Patterson DJ, Swenson J. A kinetic energy tidal generator in the northern territory-results. In: Proceedings of IECON, vol. 2. Silver Spring, MD: IEEE; 1997. p. 937–42.

[30] Blue Energy Canada Inc., Vancouver, BC, V6J 1Z0, February 2007. URL ⟨http://www.bluenergy.com/index.html⟩.
[31] Davis B. Low head tidal power: a major source of energy from the worlds oceans. In: Proceedings of the 32nd intersociety energy conversion engineering conference, IECEC-97, vol. 3; 1997. p. 1982–9.
[32] Davis BV. Water turbine model trials to demonstrate the feasibility of extracting kinetic energy from river and tidal currents. Technical Report NEL-002, Nova Energy Limited Report for National Research Council of Canada, 1980.
[33] Alternative Hydro Solutions Ltd., Toronto, Ontario, M5A4S7, August 2006. URL ⟨http://www.althydrosolutions.com⟩.
[34] Environmental Turbine Technology development, ETTE Elektro, Norway, August 2006. URL ⟨http://www.ette.no/hydro/micrhtur.htm⟩.
[35] Kirke B. Developments in ducted water current turbines, tidal paper 16-08-03 1, August 2005. URL ⟨http://www.cyberiad.net/tide.htm⟩.
[36] Kiho S, Shiono M, Suzuki K. The power generation from tidal currents by darrieus turbines. In: Proceedings of the world renewable energy congress, vol. 2. Denver, Colorado, USA; 1996. p. 1242–5.
[37] Kihon S, Shiono M. Electric power generations from tidal currents by darrieus turbine at kurushima straits. Trans IEE Japan 1992;112-D(6):530–8.
[38] Kiho S, Suzuki K, Shiono M. Study on the power generation from tidal currents by darrieus turbine. In: Proceedings of the international offshore and polar engineering conference, vol. 1; 1996. p. 97–102.
[39] Shiono M, Suzuki K, Kiho S. Output characteristics of darrieus water turbine with helical blades for tidal current generations. In: Proceedings of the international offshore and polar engineering conference, vol. 12; 2002. p. 859–64.
[40] Shiono M, Suzuki K, Kiho S. An experimental study of the characteristics of a darrieus turbine for tidal power generation. Electr Eng Japan 2000;132(3).
[41] Nilsson K, Segergren E, Leijon M. Simulation of direct drive generators designed for underwater vertical axis turbines. In: Proceedings of the fifth European wave energy conference, Cork, Ireland; 2003.
[42] Qinetiq Ltd., Cycloidal tidal power generation—phase 1. Technical Report T/06/00229/REP/1, Report for DTI Technology Program, Qinetiq Ltd., UK, 2004.
[43] Camporeale SM, Magi V. Streamtube model for analysis of vertical axis variable pitch turbine for marine currents energy conversion. Energy Conversion Manage 2000;41:1811–27.
[44] GCK Technology Inc., San Antonio, Texas 78205, USA, February 2007. URL ⟨http://www.Gcktechnology.Com/Gck/⟩.
[45] Gorban AN, Gorlov AM, Silantyev VM. Limits of the turbine efficiency for free fluid flow. J Energy Resources Technol ASME 2001;123:311–7.
[46] Portnov GG, Palley IZ. Application of the theory of naturally curved and twisted bars to designing Gorlov's helical turbine. Mech Composite Mater 1998;34(4):343–54.
[47] Florida Hydro Ltd., Palatka, FL 32177, USA, September 2006. URL ⟨http://www.floridahydro.com/⟩.
[48] Fluid Engineering Laboratory for Energy and Environment, Department of Mechanical Engineering, Faculty of Engineering, Mie University, 1515 Kamihama-cho, Tsu-shi, Mie 514-8507, Japan, August 2006. URL ⟨http://www.fel.mach.mie-u.ac.jp/posterseng2.htm⟩.
[49] Taylor GW, Burns JR, Kammann SM, Powers WB, Welsh TR. The energy harvesting eel: a small subsurface ocean/river power generator. IEEE J Oceanic Eng 2001;26(4).
[50] Kroeber L, Transverpello, Hermann-Vogel-Strasse, Munich, Germany, August 2005. URL ⟨http://www.transverpello.de⟩.
[51] Visaisouk S, Turnham BD, O'Brien RN. Electric power from salinity gradients by reverse electrodialysis. In: Proceedings of energy developments, new forms, renewables, conservations, The Global Energy Forum; 1984. p. 143–5.
[52] Ponta F, Dutt GS. An improved vertical-axis water-current turbine incorporating a channelling device. Renew Energy 2000;20(2):223–42 ISSN 0960-1481.
[53] Bayandor J, Abanteriba S, Bates I. An advanced zero-head hydro-propulsion. Renew Energy 2001;24(3–4):475–84.
[54] Bayandor J, Abanteriba S, Bates I. Principles of a new zero head hydro-propulsive system. In: Proceedings of the 34th joint power generation conference, vol. 2. New York: ASME; 1999. p. 615–20.
[55] Bahaz AS, Myers LE. Fundamentals applicable to the utilisation of marine current turbines for energy production. Renew Energy 2003;28:2205–11.

[56] UNIDO, WHO, UNEP, Regional Commissions, World Bank, Developing energy to meet development needs, January 2003. URL ⟨http://www.unesco.org/water/wwap/wwdr/pdf/chap10.pdf⟩.
[57] Zwolinski Z. 3g on w3, August 2006. URL ⟨http://www.staff.amu.edu.pl/~zbzw/glob/glob1.htm⟩.
[58] Verdant Power Canada ULC., Technology evaluation of existing and emerging technologies—water current turbines for river applications. Technical Report NRCan-06-01071, Natural Resources Canada, June 2006.
[59] Bedard R. Survey and characterization—tidal in stream energy conversion (TISEC) devices. Technical Report EPRI-TP-004NA, EPRI, November 2005.